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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The final technical report on research performed under the ONR Contract "Funda- mental Studies of Photon Statistics", emphasizes some of the most interesting results obtained. They deal with non-classical interference, violations of locality, and the determination of the time interval between two photons with femtosecond accuracy. Some possibilities for a new type of optical communication channel were explored. The research resulted in 62 publications and 88 lectures or papers presented at scientific meetings and seminars. These are all listed. Seven gradu- ate students completed Ph.D. degrees with support from the ONR Contract.		

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FINAL TECHNICAL REPORT

Contract No. N00014-83-K-0576

"Fundamental Studies of Photon Statistics"

under the direction of

Leonard Mandel

Department of Physics and Astronomy  
University of Rochester  
Rochester, New York 14627

during the period

August 1, 1983 to September 30, 1989

January 1990

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### Abstract

The Final Technical Report on research performed under the ONR Contract N00014-83-K-0576 "Fundamental Studies of Photon Statistics" emphasizes some of the most interesting results obtained. They deal with non-classical interference, violations of locality, and the determination of the time interval between two photons with femtosecond accuracy. Some possibilities for a new type of optical communication channel were explored.

The research resulted in 62 publications and 88 lectures or papers presented at scientific meetings and seminars. These are all listed. Seven graduate students completed Ph.D. degrees with support from the ONR Contract.



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## FINAL TECHNICAL REPORT

### 1. Introduction

This is the final report on research supported by the U.S. Office of Naval Research under Contract No. N00014-83-K-0576 with the title "Fundamental Studies of Photon Statistics" during the period August 1, 1983 to September 30, 1989, under the direction of Leonard Mandel.

The research resulted in 62 publications, which have either appeared or are currently in press. They are listed in Section 2 below. Also during the same period 88 lectures or papers describing the research were presented at scientific meetings or seminars. They are listed in Section 3 below.

Seven graduate students completed their Ph.D. research with partial support under the contract, and nine others received some support from the same source but have not yet finished. The Ph.D. students who completed are listed in Section 4 below, which also includes an indication of where the students went from here.

The research covered experimental and theoretical work on photon statistics of lasers and light amplifiers, creation of non-classical states in non-linear optics, two-photon correlations in parametric down-conversion, coherence properties and bistability of ring lasers, quantum interference and tests of quantum locality violations, new techniques for measuring time intervals between two photons with femtosecond accuracy, phase memory effects in entangled quantum states, squeezed states and optical communication.

Among the most interesting results are the demonstration of interference effects between photon pairs that cannot be explained classically (publication no. 30, 50, 53, 59), observations of polarization correlations that violate both classical wave optics and the particle picture of light (publ. no. 27,

31, 41), and the measurement of the average time interval between two light pulses, each of which consists of exactly one photon, with an accuracy better than one optical period (publ. no. 33, 42, 51). The last experiments show that even though a photon can never be localized precisely in time in the sense that the wave packet has no spread, yet the center of the wave packet can apparently be determined with an accuracy far shorter than the optical period.

Although most of the work dealt with fundamental questions, many of these are closely related to practical problems relating to the detection and amplification of very weak optical signals (publ. no. 3, 12).

During the period of the contract the Principal Investigator was awarded the Thomas Young Medal and Prize by the (British) Institute of Physics for outstanding contributions to quantum optics.

## 2. Publications

1. "Photon Statistics of the Linear Amplifier", with S. Friberg, in Coherence and Quantum Optics V, eds. L. Mandel and E. Wolf (Plenum, New York, 1984) p. 465.
2. "Production of Squeezed States by Combination of Parametric Down-Conversion and Harmonic Generation", with S. Friberg, Opt. Commun. **48**, 439 (1984).
3. "Proposal for Almost Noise-Free Optical Communication under Conditions of High Background", J. Opt. Soc. Am. B **1**, 108 (1984).
4. "Photon Statistics of a Dye Laser far below Threshold", with P. Lett and R. Short, Phys. Rev. Lett. **52**, 341 (1984).
5. "Theory of Parametric Frequency Down Conversion of Light", with C.K. Hong, Phys. Rev. A **31**, 2409 (1985).
6. "Conditions for Non-Classical Behavior in the Light Amplifier", with C.K. Hong and S. Friberg, J. Opt. Soc. Am. B **2**, 494 (1985).
7. "Higher Order Squeezing of a Quantum Field", with C.K. Hong, Phys. Rev. Lett. **54**, 323 (1985).
8. "Measurement of Time Delays in the Parametric Production of Photon Pairs", with S. Friberg and C.K. Hong, Phys. Rev. Lett. **54**, 2011 (1985).
9. "Generation of Higher Order Squeezing of Quantum Electromagnetic Fields", with C.K. Hong, Phys. Rev. A **32**, 974 (1985).
10. "Intensity Dependence of the Normalized Intensity Correlation Function in Parametric Down-Conversion", with S. Friberg and C.K. Hong, Opt. Commun. **54**, 311 (1985).
11. "Investigation of Time-Dependent Correlation Properties of the Bidirectional Dye Ring Laser", with P. Lett, J. Opt. Soc. Am. B **2**, 1615 (1985).
12. "Optical Communication Channel Based on Coincident Photon Pairs", with C.K. Hong and S.R. Friberg, Appl. Opt. **24**, 3877 (1985).
13. "Dwell Times and Average First Passage Times in the Dye Ring Laser", with P. Lett, in Optical Instabilities, eds. R.W. Boyd, M.G. Raymer and L.M. Narducci (Cambridge University Press, 1986) p. 367.
14. "A Test for Higher Order Squeezing of a Quantum Electromagnetic Field", with C.K. Hong, in Coherence, Cooperation and Fluctuations, eds. F. Haake, L.M. Narducci and D.F. Walls (Cambridge University Press, 1986) p. 254.
15. "Experimental Realization of a Localized One-Photon State", with C.K. Hong, Phys. Rev. Lett. **56**, 58 (1986).

16. "Non-Classical States of the Electromagnetic Field", *Physica Scripta* T12, 34 (1986).
17. "Quantum Effects in Spontaneous Parametric Down-Conversion of Light", in *Frontiers in Quantum Optics*, eds. E.R. Pike and S. Sarkar (Adam Hilger, Bristol and Boston, 1986) p. 318.
18. "Reply to "Jackiw State and Higher-Order Squeezing of the Electromagnetic Field"" with C.K. Hong, *Phys. Rev. A* 33, 4432 (1986).
19. "Relationship between Jones and Mueller Matrices for Random Media", with K. Kim and E. Wolf, *J. Opt. Soc. Am. A* 4, 433 (1986).
20. "Interference of Two Photons in Parametric Down-Conversion", with R. Ghosh, C.K. Hong and Z.Y. Ou, *Phys. Rev. A* 34, 3962 (1986).
21. "Nature of the Interference Pattern Produced on Reflection at a Phase-Conjugate Mirror", with R.W. Boyd, T.M. Habashy, A.A. Jacobs, M. Nieto-Vesperinas, W.R. Tompkin and E. Wolf, *Opt. Lett.* 12, 42 (1987).
22. "Frequency Dependence of a Ring Laser with Backscattering", with W.R. Christian, *Phys. Rev. A* 34, 3932 (1986).
23. "Chaos in a Good Cavity Single-Mode Dye Laser Due to Turbulent Dye Flow", with T.H. Chyba, E.C. Gage, R. Ghosh, P. Lett and I. McMackin, *Opt. Lett.* 12, 422 (1987).
24. "Reducing the Effects of Backscattering on the Behavior of a Ring Laser", with W.R. Christian and E.C. Gage, *Opt. Lett.* 12, 328 (1987).
25. "Coherence Properties of Squeezed Light and the Degree of Squeezing", with Z.Y. Ou and C.K. Hong, *J. Opt. Soc. Am. B* 4, 1574 (1987).
26. "Detection of Squeezed States by Cross-Correlation", with Z.Y. Ou and C.K. Hong, *Phys. Rev. A* 36, 293 (1987).
27. "Violations of Locality in Correlation Measurements with a Beam Splitter", with Z.Y. Ou and C.K. Hong, *Phys. Lett. A* 122, 11 (1987).
28. "Relation between Input and Output States for a Beam Splitter", with Z.Y. Ou and C.K. Hong, *Opt. Commun.* 63, 118 (1987).
29. "Allowed Detuning Range of the Third Order Laser Theory for an Inhomogeneously Broadened Laser", with W.R. Christian, *Opt. Commun.* 64, 537 (1987).
30. "Observation of Non-Classical Effects in the Interference of Two Photons", with R. Ghosh, *Phys. Rev. Lett.* 59, 1903 (1987).
31. "Proposal for a New Test of Bell's Inequality in an Optical Interference Experiment", with Z.Y. u and C.K. Hong, *Opt. Commun.* 67, 159 (1988).

32. "Investigation of Backscattering Effects on the Correlation Properties of a He:Ne Ring Laser", with W.R. Christian, J. Opt. Soc. Am. B 5, 1406 (1988).
33. "Measurement of the Subpicosecond Time Intervals between Two Photons by Interference", with C.K. Hong, Z.Y. Ou, Phys. Rev. Lett. 59, 2044 (1987).
34. "Interference between a Fluorescent Photon and a Classical Field: An Example of Non-Classical Interference", with C.K. Hong and Z.Y. Ou, Phys. Rev. A 37, 3006 (1988).
35. "Angular Sensitivity of a Vacuum Photodiode or Does a Photodetector always Count Absorbed Photons?", with T.H. Chyba, J. Opt. Soc. Am. B 5, 1305 (1988).



36. "Observation of Random  $\pi$  Phase Jumps in a Ring Laser with Backscattering", with W.R. Christian, T.H. Chyba and E.C. Gage, Opt. Commun. 66, 238 (1988).
37. "Derivation of Reciprocity Relations for a Beam Splitter from Energy Balance", with Z.Y. Ou, Am. J. Phys. 57, 66 (1989).
38. "Relation between Photon Statistics and Pumping Fluctuations in a Dye Laser", with T.S. Kim and E.C. Gage, J. Opt. Soc. Am. B 5, 1596 (1988).
39. "Non-Classical Photon Interference Effects", with C.K. Hong and Z.Y. Ou, in Photon and Quantum Fluctuations, eds. E.R. Pike and H. Walther, (Adam Hilger, Bristol and Philadelphia, 1988) p. 51.
40. "Measurement of the Pancharatnam Phase for a Light Beam", with T.H. Chyba, L.J. Wang and R. Simon, Opt. Lett. 13, 562 (1988).
41. "Violation of Bell's Inequality and Classical Probability in a Two-Photon Correlation Experiment", with Z.Y. Ou, Phys. Rev. Lett. 61, 50 (1988).
42. "Observation of Spatial Quantum Beating with Separated Photodetectors", with Z.Y. Ou, Phys. Rev. Lett. 61, 54 (1988).
43. "Investigation of Dye Ring Laser Statistics with Controlled Asymmetry", with E.C. Gage, Phys. Rev. A 38, 5166 (1988).
44. "Reduction of the Effects of Backscattering in a He:Ne Ring Laser by Increased Loss and Gain", with L.J. Wang, Opt. Commun. 68, 357 (1988).
45. "Fourth Order Interference Technique for Determining the Coherence Time of a Light Beam", with Z.Y. Ou, E.C. Gage and B.E. Magill, J. Opt. Soc. Am. B 6, 100 (1989).
46. "Observation of Beating between Blue and Green Light", with Z.Y. Ou, E.C. Gage and B.E. Magill, Opt. Commun. 69, 1 (1988).
47. "Response of a Phase Conjugate Mirror to an Incident Photon", with Z.Y. Ou and S. Bali, Phys. Rev. A 39, 2509 (1989).
48. "Hysteresis Effects in the Dye Ring Laser", with E.C. Gage, J. Opt. Soc. Am. B 6, 287 (1989).
49. "Propagation of Thermal Light through a Dispersive Medium", with L.J. Wang and B.E. Magill, J. Opt. Soc. Am. B 6, 964 (1989).
50. "Further Evidence of Non-Classical Behavior in Optical Interference", with Z.Y. Ou, Phys. Rev. Lett. 62, 2941 (1989).
51. "Determination of the Average Time Interval between Two Photons with Sub-Optical Period Accuracy", with Z.Y. Ou, Physics Today 42, S-57-58, (1989).

52. "Anomalous Bistable Behavior of a Dye Laser", with E.C. Gage and F. Cheng, J. Opt. Soc. Am. B 6, 1383 (1989).
53. "Vacuum Effects on Interference in Two-Photon Down-Conversion", with Z.Y. Ou and L.J. Wang, Phys. Rev. A 40, 1428 (1989).
54. "Photon-Antibunching and Sub-Poissonian Photon Statistics", with X. Zou, Phys. Rev. A 41, 475 (1990).
55. "Evidence for Phase Memory in Two-Photon Down-Conversion through Entanglement with the Vacuum", with Z.Y. Ou, L.J. Wang and X.Y. Zou, Phys. Rev. A (to be published).
56. "Behavior of a Ring Laser with Injected Signal near Threshold", with F.C. Cheng, in Coherence and Quantum Optics VI, eds. J.H. Eberly, L. Mandel and E. Wolf (Plenum, New York, to be published) p. 126.
57. "Investigation of  $\pi$  Phase Jumps in a Ring Laser", with T.H. Chyba, in Coherence and Quantum Optics VI, eds. J.H. Eberly, L. Mandel and E. Wolf (Plenum, New York, to be published). p. 142.
58. "Optical Phase Information Due to the Vacuum in Two-Photon Down-Conversion", with Z.Y. Ou, L.J. Wang and X.Y. Zou, in Coherence and Quantum Optics VI, eds. J.H. Eberly, L. Mandel and E. Wolf (Plenum, New York, to be published) p. 729.
59. "Observation of Nonlocal Interference in Separated Photon Channels", with Z.Y. Ou, X.Y. Zou and L.J. Wang, Phys. Rev. Lett. (to be published).
60. "Non-Local and Non-Classical Effects in Two-Photon Down-Conversion", with Zhe-Yu Ou, Quantum Optics (to be published).
61. "Coherence in Two-Photon Down-Conversion Induced by a Laser", with Z.Y. Ou, L.J. Wang, X.Y. Zou, Phys. Rev. A (to be published).
62. "Photon Amplification by Parametric Down-Conversion", with Z.Y. Ou, L.J. Wang and X.Y. Zou, J. Opt. Soc. Am. B (to be published).

### 3. Lectures

1. "Introduction to Lasers"  
L. Mandel  
University Forum "Lasers in the Eighties"  
University of Rochester, Rochester, New York  
October 4, 1983
2. "Investigation of Two-Time Correlations in a Dye Ring Laser"  
S. Friberg, P. Lett and L. Mandel  
Optical Society of America, New Orleans, Louisiana  
October 18, 1983
3. "Computer Solutions of the Two-Mode Laser Equations with Additive and Multiplicative Noise"  
R. Short, P. Lett and L. Mandel  
Optical Society of America, New Orleans, Louisiana  
October 18, 1983
4. "Observation of Sub-Poissonian Photon Statistics in Resonance Fluorescence"  
R. Short  
Quantum Optics Seminar, Dept. of Physics and Astronomy  
University of Rochester, Rochester, New York  
October 25, 1983
5. "Are Photons for Real?" (Invited)  
L. Mandel  
Award Winners Session of The Industrial Associates Meeting  
Institute of Optics  
University of Rochester, Rochester, New York  
November 15, 1983
6. "Evidence for the Quantum Nature of Light"  
L. Mandel  
Department of Physics Colloquium  
University of Arkansas, Fayetteville, Arkansas  
November 18, 1983
7. "Some Current Research in Quantum Optics"  
L. Mandel  
Department of Physics Seminar  
University of New Mexico, Albuquerque, New Mexico  
January 6, 1984

8. "Discontinuous Phase Transition in the Dye Ring Laser" (Invited)  
L. Mandel  
Workshop on The Physics of Optical Ring Gyros  
Snowbird, Utah  
January 8, 1984
  
9. "The Quantum Statistics of Light"  
L. Mandel  
Department of Physics Colloquium  
Johns Hopkins University, Baltimore, Maryland  
March 8, 1984
  
10. "Photon Statistics and the Quantum Nature of Light"  
L. Mandel  
Department of Physics Colloquium  
University of Toronto, Toronto, Canada  
March 22, 1984
  
11. "Sub-Poissonian Photon Statistics and Squeezed Quantum States"  
L. Mandel (Invited)  
International Quantum Electronics Conference (IQEC '84)  
Anaheim, California  
June 20, 1984
  
12. "Non-Classical Coherence and Squeezing in the Laser Amplifier"  
L. Mandel (Invited)  
U.S.-Japan Bilateral Seminar on Coherence, Incoherence and Chaos  
Nara, Japan  
September 1, 1984
  
13. "The Photoelectric Effect and the Quantum Nature of Light" (Invited)  
L. Mandel  
DuBridge Symposium at The American Physical Society Meeting (New  
York State Section)  
Rochester, New York  
September 21, 1984
  
14. "Time-Resolved Two-Photon Correlations in Parametric Down-  
Conversion"  
S. Friberg and L. Mandel  
Optical Society of America, San Diego, California  
November 2, 1984

15. "Time-Resolved Correlation Measurements of a Dye Ring Laser"  
P. Lett and L. Mandel  
 Optical Society of America, San Diego, California  
 November 2, 1984
  
16. "The Quantum Statistics of Light" (Invited)  
 L. Mandel  
 Lasers '84 International Conference, San Francisco, California  
 November 28, 1984
  
17. "Research in Quantum Optics"  
 L. Mandel  
 Department of Physics and Astronomy (Informal Talk)  
 University of Rochester, Rochester, New York  
 March 23, 1985
  
18. "The Quantum Statistics of Light"  
 L. Mandel  
 Department of Physics Colloquium  
 The City College of the CUNY, New York, N.Y.  
 May 1, 1985
  
19. "The Laser - Twenty-Five Years Old" (Invited)  
 L. Mandel  
 NSF 1985 Summer Honors Workshop for Science Teachers  
 University of Rochester, Rochester, New York  
 July 8, 1985
  
20. "Photon Correlations and Spontaneous Parametric Down-Conversion"  
 S.R. Friberg  
 Seminar at Communications and Research Institute  
 AT&T Bell Laboratories, Holmdel, New Jersey  
 July 16, 1985
  
21. "Photon Correlations and Spontaneous Parametric Down-Conversion"  
 S.R. Friberg  
 Department of Physics Seminar  
 University of Lowell, Lowell, Massachusetts  
 July 17, 1985
  
22. "Photon Correlations and Spontaneous Parametric Down-Conversion"  
 S.R. Friberg  
 Quantum Optics Seminar, Dept. of Physics and Astronomy  
 University of Rochester, Rochester, New York  
 September 10, 1985

23. "Non-Classical Photon Statistics and Squeezed States" (Invited)  
L. Mandel  
Seventh National Quantum Electronics Conference  
Gt. Malvern, United Kingdom  
September 18, 1985
24. "Non-Classical Photon Statistics" (Invited)  
L. Mandel  
Workshop on New Trends in Quantum Optics and Electrodynamics  
Rome, Italy  
October 3, 1985
25. "Correlation Properties of the Ring Laser with Backscattering"  
W.R. Christian and L. Mandel  
Optical Society of America, Washington, D.C.  
October 15, 1985
26. "Intensity Correlations in Parametric Down-Conversion"  
S.R. Friberg and L. Mandel  
Optical Society of America, Washington, D.C.  
October 15, 1985
27. "An Optical Communication Channel Based on Coincident Photon Pairs"  
C.K. Hong, S.R. Friberg and L. Mandel  
Optical Society of America, Washington, D.C.  
October 17, 1985
28. "Higher Order Squeezing of an Optical Field"  
C.K. Hong and L. Mandel  
Optical Society of America, Washington, D.C.  
October 18, 1985
29. "A Test for Higher Order Squeezing of a Quantum Electromagnetic Field" (Invited)  
L. Mandel  
Symposium on Statistical Physics, Quantum Optics and Nuclear Physics (In honor of R.J. Glauber)  
Harvard University, Cambridge, Massachusetts  
October 19, 1985

30. "Higher Order Squeezing of a Quantum Field" (Invited)  
 L. Mandel  
 Workshop on Squeezed States of Light  
 Massachusetts Institute of Technology, Cambridge, Mass.  
 October 21, 1985
  
31. "Quantum Statistics of Light"  
 L. Mandel  
 Dept. of Physics Colloquium  
 Yale University, New Haven, Connecticut  
 November 1, 1985
  
32. "Non-Classical States of the Radiation Field. I." (Invited)  
 L. Mandel  
 Symposium on Quantum Fields and Modern Spectroscopy  
 Niels Bohr Institute, Copenhagen, Denmark  
 November 12, 1985
  
33. "Non-Classical States of the Radiation Field. II." (Invited)  
 L. Mandel  
 Symposium on Quantum Fields and Modern Spectroscopy  
 Niels Bohr Institute, Copenhagen, Denmark  
 November 13, 1985
  
34. "Quantum Effects in Spontaneous Parametric Down-Conversion of Light"  
 L. Mandel (Invited)  
 Symposium on Frontiers in Quantum Optics  
 Malvern, England,  
 December 20, 1985
  
35. "Intensity Correlations, First Passage Times and "No Chaos" in Dye  
 Lasers"  
 P. Lett  
 Quantum Optics Seminar, Dept. of Physics and Astronomy  
 University of Rochester, Rochester, New York  
 April 15, 1986
  
36. "The Quantum Statistics of Light"  
 L. Mandel  
 Theoretical Division Seminar  
 Los Alamos National Laboratory, Los Alamos, New Mexico  
 May 22, 1986

37. "A Pedestrian's Guide to Squeezed States" (Invited)  
L. Mandel  
XIV International Conference on Quantum Electronics (IQEC '86)  
San Francisco, California  
June 10, 1986
38. "Non-Local Effects in the Photoelectric Detection of Light"  
L. Mandel  
XIV International Conference on Quantum Electronics (IQEC '86)  
San Francisco, California  
June 10, 1986
39. "Dye Lasers: Quantum Optics and Nonlinear Dynamics"  
P. Lett  
Seminar at National Bureau of Standards  
Gaithersburg, Maryland  
July 14, 1986
40. "Dye Lasers: Quantum Optics and Nonlinear Dynamics"  
P. Lett  
Seminar at Joint Institute for Laboratory Astrophysics (JILA)  
University of Colorado, Boulder, Colorado  
July 23, 1986
41. "Dye Lasers: Quantum Optics and Nonlinear Dynamics"  
P. Lett  
Seminar at IBM Almaden Research Center  
San Jose, California  
July 24, 1986
42. "Dye Lasers: Quantum Optics and Nonlinear Dynamics"  
P. Lett  
Department of Physics Seminar  
Lehigh University, Bethlehem, Pennsylvania  
July 29, 1986
43. "An Introduction to Chaos: Its Methods and Its Madness"  
P. Lett  
Colloquium at Center for Basic Standards  
National Bureau of Standards, Gaithersburg, Maryland  
September 17, 1986



44. "Light Fluctuations in the Laser" (Invited)  
L. Mandel  
Optical Society of America and International Laser Science Meeting  
Seattle, Washington  
October 21, 1986
  
45. "Theory of Two-Photon Interference in Down-Conversion"  
R. Ghosh, C.K. Hong, Z.Y. Ou and L. Mandel  
Optical Society of America, Seattle, Washington  
October 21, 1986
  
46. "Effect of Crystal Length on the Correlation Times of Down-Converted Photons"  
C.K. Hong, Z.Y. Ou and L. Mandel  
Optical Society of America, Seattle, Washington  
October 21, 1986
  
47. "Detuning and Instability Effects in a He:Ne Ring Laser with Backscattering"  
W.R. Christian and L. Mandel  
Optical Society of America, Seattle, Washington  
October 24, 1986
  
48. "Probability Distributions of the Light Intensity in the Dye Laser"  
E.C. Gage, P. Lett and L. Mandel  
Optical Society of America, Seattle, Washington  
October 24, 1986
  
49. "Squeezed States in Quantum Optics: A Guide for Pedestrians"  
L. Mandel  
Colloquium at IBM Thomas J. Watson Research Center  
Yorktown Heights, New York  
November 18, 1986
  
50. "Effects of Backscattering on the Statistical Properties of a He:Ne Ring Laser"  
William R. Christian  
Seminar at Singer-Kearfott Div., Little Falls, New Jersey  
March 10, 1987
  
51. "Violation of Locality in the Interference of Two Photons"  
R Ghosh and L. Mandel  
International Quantum Electronics Conference, Baltimore, Maryland  
April 30, 1987

52. "Detecting Squeezed States by Cross-Correlation" (Invited)  
L. Mandel  
U.S.-Japan Seminar, Monterey, California  
July 23, 1987
53. "Effect of Backscattering on the Fluctuation Properties of a He-Ne Ring Laser"  
William R. Christian  
Seminar at Rockwell International Corp. Science Center  
Thousand Oaks, California  
September 10, 1987
54. "Homogeneous Squeezing, Spectral Component Squeezing and the Degree of Squeezing"  
C.K. Hong, Z.Y. Ou and L. Mandel  
Optical Society of America, Rochester, New York  
October 19, 1987
55. "Relationship between Quantum States at the Input and Output of a Beam Splitter"  
C.K. Hong, Z.Y. Ou and L. Mandel  
Optical Society of America, Rochester, New York  
October 20, 1987
56. "Proposal for a New Test of Locality in a Two-Photon Interference Experiment"  
Z.Y. Ou, C.K. Hong and L. Mandel  
Optical Society of America, Rochester, New York  
October 22, 1987
57. "Domain of the Third Order Theory of a Detuned, Inhomogeneously Broadened Laser"  
W.R. Christian and L. Mandel  
Optical Society of America, Rochester, New York  
October 23, 1987
58. "Effect of Backscattering on the Fluctuation Properties of a He:Ne Ring Laser"  
W.R. Christian and L. Mandel  
Optical Society of America, Rochester, New York  
October 23, 1987

59. "Effect of Varying Asymmetry on a Dye Ring Laser"  
E.C. Gage and L. Mandel  
 Optical Society of America, Rochester, New York  
 October 23, 1987
  
60. "Does a Photodetector Measure the Light Intensity or the Energy Flux?"  
T.H. Chyba and L. Mandel  
 Optical Society of America, Rochester, New York  
 October 23, 1987
  
61. "Proposal for Reducing the Effects of Backscattering on a Ring Laser"  
 W.R. Christian, E.C. Gage and L. Mandel  
 Third International Laser Science Conference  
 Atlantic City, New Jersey  
 November 4, 1987
  
62. "Interference Effects in Non-Classical States of Light"  
 L. Mandel  
 Colloquium at Naval Research Lab., Washington, D.C.  
 December 16, 1987
  
63. "Non-Classical Interference Effects in Optics"  
 L. Mandel  
 Colloquium at Institute of Optics, University of Rochester  
 Rochester, New York  
 January 20, 1988
  
64. "Non-Classical Photon Interference Effects" (Invited)  
C.K. Hong, Z.Y. Ou and L. Mandel  
 NATO Advanced Workshop on Squeezed and Non-Classical Light  
 Cortina, Italy  
 January 21, 1988
  
65. "Quantum Effects in the Interference of Light" (Invited)  
 L. Mandel  
 Spring Meeting of the American Physical Society  
 Baltimore, Maryland  
 April 19, 1988
  
66. "Experimental Localization of a Photon in Space and Time" (Invited)  
 L. Mandel  
 International Symposium on Spacetime Symmetries (in honor of  
 Prof. Eugene Wigner)  
 University of Maryland, College Park, Maryland  
 May 24, 1988

- 67. "Quantum Effects in the Interference of Light"  
L. Mandel  
Department of Physics Colloquium, Clarkson University,  
Potsdam, New York  
September 30, 1988
  
- 68. "Quantum Effects in the Interference of Light"  
L. Mandel  
Department of Physics and Astronomy Colloquium  
Swarthmore College, Swarthmore, Pennsylvania  
October 20, 1988
  
- 69. "Observation of Spatial Beating at Near Optical Frequencies in the  
Interference of Two Photons"  
Z.Y. Ou and L. Mandel  
Optical Society of America, Santa Clara, California  
October 31, 1988
  
- 70. "Measurement of Coherence Time by Fourth-Order Interference"  
Z.Y. Ou, E.C. Gage, B.E. Magill and L. Mandel  
Optical Society of America, Santa Clara, California  
October 31, 1988
  
- 71. "Reciprocity Relations for a Beam Splitter"  
Z.Y. Ou and L. Mandel  
Optical Society of America, Santa Clara, California  
November 2, 1988
  
- 72. "Investigation of Jump Discontinuities in a Ring Laser with  
Backscattering"  
T.H. Chyba and L. Mandel  
Optical Society of America, Santa Clara, California  
November 3, 1988
  
- 73. "Fluctuation Properties of a Dye Ring Laser with Controllable  
Asymmetry"  
E.C. Gage and L. Mandel  
Optical Society of America, Santa Clara, California  
November 3, 1988

74. "Reducing the Effects of Backscattering on the Correlations of a He:Ne Ring Laser"  
L.J. Wang and L. Mandel  
 Optical Society of America, Santa Clara, California  
 November 3, 1988
  
75. "Quantum Effects in Optical Interference"  
 L. Mandel  
 Department of Physics Seminar  
 M.I.T., Cambridge, MA  
 November 29, 1988
  
76. "Fluctuation Properties of Single-Frequency Dye Lasers"  
 E.C. Gage  
 Optical Recording Division Seminar  
 Eastman Kodak Co., Rochester, NY  
 February 3, 1989
  
77. "Fluctuation Properties of Single-Frequency Dye Lasers"  
 E.C. Gage  
 Advanced Lasers Group Seminar  
 Lawrence Livermore National Lab., Livermore, CA  
 February 7, 1989
  
78. "Fluctuation Properties of Single-Frequency Dye Lasers"  
 E.C. Gage  
 Seminar at Optical Communications and Quantum Electronics Group  
 Lincoln Laboratories, MIT, Cambridge, MA  
 February 21, 1989
  
79. "Quantum Effects in the Interference of Light"  
 L. Mandel  
 Departmental Colloquium, Imperial College, U.K.  
 May 4, 1989
  
80. "Non-Classical Interference Effects in Optics" (Invited)  
 L. Mandel  
 OSA Symposium on Quantum Limited Imaging  
 N. Falmouth, Cape Cod, MA  
 June 12, 1989
  
81. "Investigation of  $\pi$  Phase Jumps in a Ring Laser"  
T.H. Chyba and L. Mandel  
 Sixth Rochester Conference on Coherence and Quantum Optics  
 University of Rochester, Rochester, NY  
 June 27, 1989

82. "Behavior of a Ring Laser with Injected Signal near Threshold"  
F.C. Cheng and L. Mandel  
Sixth Rochester Conference on Coherence and Quantum Optics  
University of Rochester, Rochester, NY  
June 27, 1989
83. "Optical Phase Information due to the Vacuum in Two-Photon Down-Conversion"  
Z.Y. Ou, L.J. Wang, X.Y. Zou and L. Mandel  
Sixth Rochester Conference on Coherence and Quantum Optics  
University of Rochester, Rochester, NY  
June 28, 1989
84. "Quantum Effects in Fourth Order Optical Interference"  
L. Mandel (Invited)  
Lecture at NTT Basic Research Labs., Tokyo, Japan  
August 16, 1989
85. "Determination of Femtosecond Time Intervals between Two Photons"  
L. Mandel (Invited)  
Lecture at NTT Basic Research Labs., Tokyo, Japan  
August 18, 1989
86. "Locality Violations and Phase Memory in Two-Photon Down-Conversion"  
L. Mandel (Invited)  
Lecture at NTT Basic Research Labs., Tokyo, Japan  
August 23, 1989
87. "Non-Local and Non-Classical Effects in Two-Photon Down-Conversion"  
Zhe-Yu Ou and L. Mandel (Invited)  
3rd International Symposium on Foundations of Quantum Mechanics  
Tokyo, Japan  
August 30, 1989
88. "Quantum Effects in Optical Interference"  
L. Mandel  
Optical Sciences Center Colloquium,  
University of Arizona, Tucson, AZ,  
September 21, 1989

4. Students who completed Ph.D. degrees during the Contract period

<u>Name</u>	<u>Date</u>	<u>Employer</u>
R.C. Short	Nov. 1983	Eastman Kodak Research Labs. Rochester, NY
S.R. Friberg	Nov. 1985	NTT Basic Research Labs., Tokyo, Japan
P.D. Lett	Oct. 1986	National Institute of Standards and Technology (NBS), Gaithersburg, MD
R. Ghosh	July 1987	Asst. Prof. of Physics, J. Nehru U., New Delhi, India
W.R. Christian	Nov. 1987	Rockwell International Science Center Thousand Oaks, CA
C.K. Hong	Apr. 1988	Lawrence Livermore National Lab./UC, Berkeley (Post-Doc. Res. Assoc.)
E.C. Gage	Apr. 1989	Eastman Kodak Research Labs. Rochester, NY